

# Junction temperature measurement of alternating current light-emitting-diode by threshold voltage method

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**Abstract** Junction temperature of alternating current light-emitting-diode (AC-LED) has a significant effect on its stable light output and lifetime. The threshold voltage measurement is employed to characterize the junction temperature of AC-LED, due to its excellent merits in high efficiency and accuracy. The threshold voltage is measured when the driving current of an AC-LED rises to a reference on-set value from the zero-crossing node. Based on multiple measurements of threshold voltage at different temperatures, a linear relationship was uncovered between the threshold voltage and the junction temperature of AC-LED with the correlating factor of temperature sensitive parameter (TSP). Thereby, we can calculate the junction temperature with the TSP and threshold voltage once the AC-LED stays at thermal equilibrium state. The accuracy of the proposed junction temperature measurement technique was found to be  $\pm 3.2^\circ\text{C}$  for the reference current of 1 mA. It is concluded that the method of threshold voltage is accurate and simple to implement, making it highly suitable for measuring the junction temperature of AC-LED in industry.

**Keywords** optoelectronics, junction temperature measurement, threshold voltage method, alternating current light-emitting-diode (AC-LED)

## 1 Introduction

Light-emitting diodes (LEDs) are becoming popular as a type of energy-efficient and long-lifetime solid state light source for many applications in our daily life, ranging from general lighting, architecture decoration, industrial and medical illumination, backlighting projection, signs and displays, etc. To be driven by alternating line power, LED

lamps often have to be equipped with external transformer and rectifier components at the cost of increased complexity and compromised reliability. The emerging alternating current LED (AC-LED) technology employs the chip architecture of micro-LED arrays, in alliance with the antiparallel or Wheatstone bridge circuitry design, eliminating the LED driver and operating the AC-LED lamps from 120 VAC/60 Hz or 240 VAC/50 Hz line voltages directly. The cost of the light sources can potentially be reduced by as much as 30%–40% while increasing the system reliability. The thermal management requirements might also be relieved in the driver-free LED lighting systems as the conventional drivers are not efficient and generate excess system heat as a result. In addition, removal of the external drivers in the LED lamps will also lead to compact volume and low weight light fixtures, making LED application in retrofitting traditional light fixtures such as table lamps, task lamps, replacement lamps (A19, PAR, etc.), chandeliers, wall sconces or ceiling fixtures as simple as changing a light bulb [1].

At present, the measurement techniques of LED junction temperatures are mainly developed for direct current LEDs (DC-LEDs). With the advent of AC-LED technology, it is essential to have a method that would be able to characterize the junction temperature of the AC-LEDs with high efficiency and accuracy. In the present work, a novel approach of threshold voltage method is proposed for junction temperature characterization of AC-LEDs. The new method was tested, and results of which were compared with the traditional peak wavelength method, showing a good agreement within  $4^\circ\text{C}$ . Further analysis suggested that the error of the threshold voltage method can be narrowed down to  $\pm 2.7^\circ\text{C}$  when the reference current is chosen as  $\sim 1$  mA. It is concluded that the method of threshold voltage is accurate and simple to implement, making it highly suitable for determining the junction temperatures of AC-LEDs in industry.

Among the existing DC-LED junction temperature

methods, the forward voltage method [2] has been identified to be the most accurate and straightforward method. The forward voltage method consists of two parts [3], calibration measurement, and the actual junction-temperature measurement. By applying a small duty cycle forward current pulse to a DC-LED sample whose temperature is under thermostat control, the forward bias voltage of a DC-LED sample is measured at different temperatures. A constant correlating factor, temperature sensitive parameter (TSP), can be determined between the voltage and temperatures within the calibration range. The following part of the method would measure a forward voltage of the DC-LED when it is at quasi-steady-state. However, due to the fact that AC-LEDs are driven by alternating current, the alternating thermal power dissipation will occur in the junction [4]. The stable forward voltage according to the reference current will not be found in this case if the junction-temperature measurement was to be performed on an AC-LED sample.

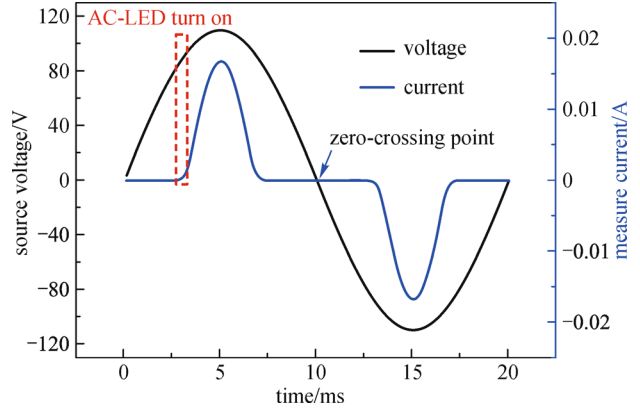
Liu et al. [5] modified the forward voltage method. They added a reference pulse current when the phase of voltage in the AC-LED reverses at the zero-crossing point, then tested the forward voltage corresponding to the pulse current. There are several issues that need to be put into consideration for the modification. First, a long pulse width of reference current is often necessary to measure the forward bias voltage accurately. It leads to a lower value of the measured temperature compared to the actual value for the LEDs [6]. Additionally, the study by Keppens et al. has suggested that TSP can only be accurately determined at a low reference pulse current [7]. The resultant low voltage signal is difficult to extract from the dynamic background of varying AC driven voltage.

Toward this end, we propose a simple and accurate method to characterize the AC-LED junction temperature. For AC-LED operation, since the micro-LEDs in the AC-LED chip will not turn on until the bias voltage across the chip reaching an onset threshold, it is possible to correlate the threshold voltage to the junction temperature via TSP calibration. Experimentally, the threshold voltage is measured at a reference current level, as shown in Fig. 1. A calibration process is used to determine the TSP by characterizing the threshold voltage of an AC-LED sample whose temperature is under thermostat control. Once the TSP value is established, with the AC-LED operating at steady-state and the junction temperature remains constant, we are able to calculate the AC-LED junction temperature from the measured threshold voltage.

## 2 Theory

### 2.1 Threshold voltage as a function of junction temperature

Theoretically, the relationship between the voltage ( $V$ ) and



**Fig. 1** Cycle voltage and current variation of an AC-LED driven by sinusoidal alternating voltage

junction temperature is governed by the Shockley equation of diode current:

$$I_{\text{diode}} = I_s \left[ \exp \left( \frac{eV}{nkT} \right) \right], \quad (1)$$

where  $k$  is Boltzmann constant,  $T$  is the absolute temperature,  $n$  is the ideality factor, and  $I_s$  is the reverse saturation current density of the semiconductor. The reverse saturation current is an equation dependent on temperature, shown in Eq. (2).

$$I_s = eA \left[ \sqrt{\frac{D_n}{\tau_n}} \frac{1}{N_D} + \sqrt{\frac{D_p}{\tau_p}} \frac{1}{N_A} \right] N_C N_V \exp \left( \frac{-E_g}{nkT} \right), \quad (2)$$

where  $A$  is the cross-sectional area of p-n junction;  $D_n$  and  $D_p$  are the diffusion constants of electrons and holes,  $\tau_n$  and  $\tau_p$  are the lifetimes of electrons and holes, respectively,  $E_g$  is the band-gap energy, and the effective density of states at the conduction band and valence band edge are  $N_C$  and  $N_V$ , respectively. For first order approximation, the minority-carrier lifetimes of  $\tau_n$  and  $\tau_p$  have been assumed to be temperature-invariant, and the full ionization assumption renders the donor and acceptor concentrations in LED p-n junctions,  $N_D$  and  $N_V$ , independent of temperature as well [8].

According to Neamen's study [9],  $D_n$  and  $D_p$  are temperature-dependent with the function of  $T^{-1/2}$ , while  $N_C$  and  $N_V$  are proportional to  $T^{3/2}$ . By defining a temperature-independent factor of  $B$ , the threshold voltage expressed as

$$B = eA \left[ \sqrt{\frac{D_n T^{\frac{1}{2}}}{\tau_n}} \frac{1}{N_D} + \sqrt{\frac{D_p T^{\frac{1}{2}}}{\tau_p}} \frac{1}{N_A} \right] N_C N_V T^{-3}, \quad (3)$$

$$V = \frac{E_g}{e} - \frac{nk}{e} \ln \left( \frac{B}{I} \right) T - \frac{nkT}{e} \ln T^r, \quad (4)$$

where  $r$  is a constant. Furthermore, since Keppens et al.

have reported that the linear relationship between  $E_g$  and  $T$  can be described with a factor  $C$  when the temperatures are higher than 300 K [7]:

$$E_g = E_0 - CT. \quad (5)$$

The TSP of the voltage with respect to the junction temperature can be determined as

$$\text{TSP} = \frac{dV}{dT} = - \left[ C + \frac{nk}{e} \ln \left( \frac{B}{I_{\text{diode}}} \right) \right]. \quad (6)$$

It is evident from Eq. (6) that, under a fixed reference current  $I_{\text{diode}}$ , the threshold voltage and junction temperature exhibit a linear relationship with the factor of TSP.

To facilitate industrial measurement, it is defined that threshold current  $I = 1$  mA, threshold voltage  $V$  is forward voltage when AC-LED forward current is 1 mA.

## 2.2 Reference threshold current selected as a fixed value

To employ the threshold voltage method to characterize the junction temperature of AC-LEDs in practice, it is necessary to define the reference current  $I$ , corresponding to the threshold voltage. The reference current has to be sufficiently low to avoid significant joule heating. Otherwise, it could lead LED temperature to exceed the calibration set point. Poppe et al. [10] mentioned in the previous studies that the junction temperature rises under  $0.5^\circ\text{C}$  in 1 ms after the LED is turned on. Nevertheless, the minimum value of the reference current level is also limited by the sampling rate and the sensitivity of the testing equipments. Our temporal analysis of the AC-LED current suggests that the reference current level of  $I = 1$  mA is an appropriate tradeoff for the 45mil power AC-LED devices under test.

## 3 Experiment apparatus

AC-LED AW3200 produced by Seoul Semiconductor is employed in this experiment. The driving voltage is 110 V and the operating power is 4.4 W with size  $18.5 \text{ mm} \times 12 \text{ mm} \times 6.5 \text{ mm}$ . The experiment uses a source-meter called Keithley 2636A which provides the source measurement unit (SMU). It is used as a current/voltage source and simultaneously measure the voltage and current flowing through the device under test. The SMU is programmed to generate a set of discrete voltages to simulate an 110 VAC/50 Hz AC power from zero phase and measure each corresponding instantaneous forward current of the sample. A thermostat oven is used to heat up the AC-LED. The sensor on the thermostat monitors the internal temperature while the testing chamber is at room temperature.

## 4 Methods

The method is broken down into two processes. The first calibration part determines the TSP of the AC-LED. The second part is to calculate the junction temperature with the TSP and threshold voltage when the AC-LED stays at steady-state.

### 4.1 Measurement of TSP

Place an AC-LED sample into the thermostat oven and set it to a certain temperature  $T_n$ . When the AC-LED junction temperature reaches  $T_n$ , operate the AC-LED by a cycle sinusoidal voltage starting from the zero phase. This cycle alternative voltage is simulated by continuous pulse voltage with the programmed SMU and at the same time, the current flowing through the sample can also be tracked with a sampling speed of 10 KS/s. More importantly, the threshold voltage could be selected. Every sinusoidal cycle will have 4 threshold voltages. The first threshold voltage in the first half of the cycle is inserted in Fig. 1 which is the only part needed in the method. The first threshold voltages of AC-LED at different temperature are recorded according to the steps above and shown in Fig. 2.

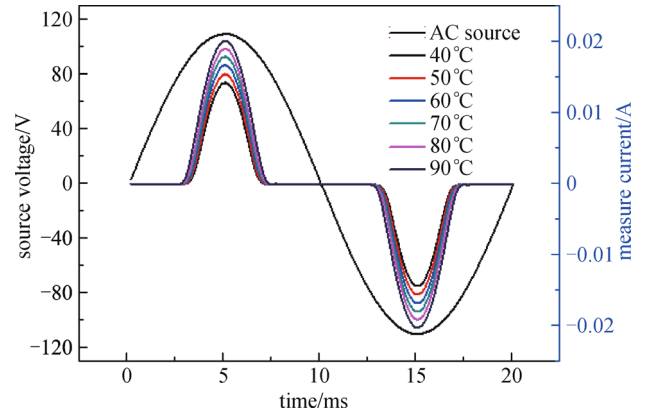


Fig. 2 Cycle forward current under a series of oven temperatures

### 4.2 Calculation of junction temperature

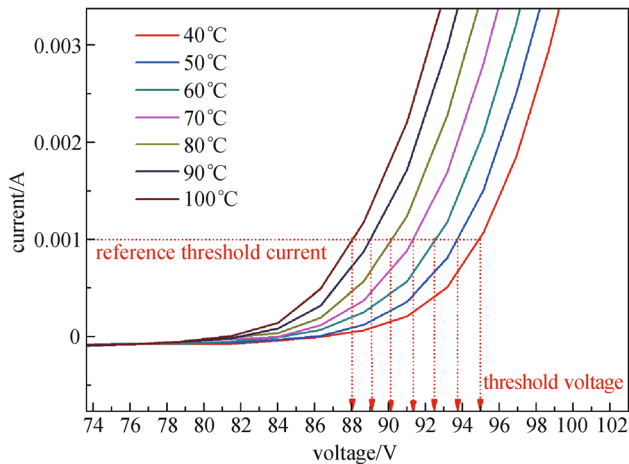
Remove the AC-LED sample from the thermostat oven and place it into a testing chamber. Once the AC-LED junction temperature decreased to the room temperature  $T_0$ , drive the sample with continuous alternative voltage and record the current at the same time. The threshold voltage  $V_0$  in the initial state and the threshold voltage  $V_j$  can be determined in the process and the relationship of the AC-LED between threshold voltages and junction temperatures could be written as Eq. (7).

$$T_j = \frac{V_j - V_0}{\text{TSP}} + T_0. \quad (7)$$

## 5 Result analysis

### 5.1 Junction temperature of AC-LED

In the experiment, a series of current variation in temperatures ranging from 40°C to 90°C are measured which is shown in Fig. 2. It is shown that the peak currents are all reached at the same time, however in the current-voltage graph in Fig. 3, the AC-LED threshold voltages vary along with the changing of temperature. The threshold current of the AC-LED is defined as  $I = 1$  mA in the experiment. The threshold voltages in different junction temperatures can be determined once the threshold current is defined. In Fig. 3, the AC-LED threshold voltage decreases while the temperature increases. The TSP value is  $-0.11$  V/°C. The threshold voltage  $V_j$  according to the threshold current value of the AC-LED is 88.4 V and the junction temperature is 97.3°C.



**Fig. 3**  $I$ - $V$  curve of AC-LED at different junction temperatures

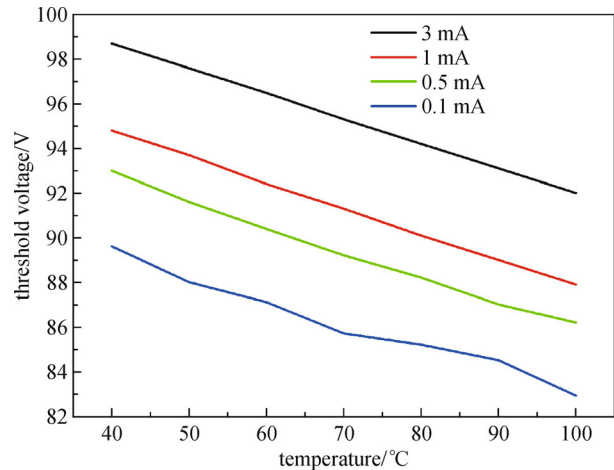
### 5.2 Reference threshold current acquisition

In Fig. 1, when the AC-LED starts working at 1 ms, the forward current reaches 4.2 mA. So the reference current should be less than 4.2 mA. In Fig. 4, the threshold voltage is plotted with the junction temperature with parameterized in 3, 1, 0.5 and 0.1 mA, respectively. Looking at Table 1, if the reference threshold current was selected as 0.1 mA, the time of joule heating would be short, however the error of the threshold voltage would be the hugest. On the other hand, if the reference current were 3 mA, the time of joule heating would be the longest and giving less error of the threshold voltage. For this experiment, the reference threshold current value is defined as 1 mA.

To verify that the method works, four other experiments were processed with the same AC-LED, TSP parameters, threshold voltages and junction temperatures shown in Table 2. It can be determined that the TSP parameters are very stable within the valid number. The value of the

**Table 1** Time of self-heating and threshold voltage maximum error under different reference threshold currents

reference threshold current/mA	time of self-heating /ms	threshold voltage maximum error/V
3	0.87	0.2
1	0.65	0.2
0.5	0.54	0.3
0.1	0.33	0.6



**Fig. 4** Correlations between threshold voltages and junction temperatures under different reference threshold currents

**Table 2** TSP parameters, threshold voltages and junction temperatures of five experiments with the same sample

number	calculated TSP parameter /( $V \cdot ^\circ C^{-1}$ )	threshold voltage in normal working /V	junction temperature /°C
1	0.11	88.2	110.0
2	0.11	88.1	100.9
3	0.11	88.4	98.2
4	0.11	88.3	99.1
5	0.11	88.0	101.8

threshold voltage has a difference between  $\pm 0.2$  V and the maximum value of the junction temperature has a difference between  $\pm 1.8$ °C. The above data shows that the repeatability of the junction temperature is well and the volatility is small.

It is suggested that the junction temperature deviation mainly depends on self-heating and the error of the threshold voltage. To avoid the junction temperature self-heating, the reference current is adopted in the AC-LED in the process of calibration. Since the junction self-heating is inevitable, the heating time is limited in 1 ms. The linearity of the TSP will lower the influence on the junction temperature under 0.5°C. It is possible to get an accurate

TSP with a small deviation and minimize the error in the experiment. When the threshold current is 1 mA, the threshold voltage uncertainty is under  $\pm 0.2$  V and the TSP calculation uncertainty is under  $\pm 0.1$  V. When the threshold voltage of the AC-LED is at steady-state, with a cumulative deviation under  $\pm 0.3$  V, the impact on the junction temperature is  $\pm 2.7^\circ\text{C}$ . In conclusion, the junction temperature accuracy in this method is  $\pm 3.2^\circ\text{C}$ .

## 6 Conclusions

The paper introduces an accurate method to measure the AC-LED junction temperature. When AC-LED is at normal state, the selected forward voltage is instantaneous. To ensure the consistency of the forward voltage in the calibration part of the method, we obtained a constant changing sinusoidal voltage. The forward voltage is defined as the threshold voltage in the initial state of the AC-LED. With that being defined, the junction self-heating could be minimized. We found that the maximum error comes from not only the uncertainty of the threshold voltage, but also ultimately from the uncertainty of the current. For this experiment, the sample rate of the meter is only 10 KS/s. To get a higher accuracy in the results, it would require increasing the rate of the meter.

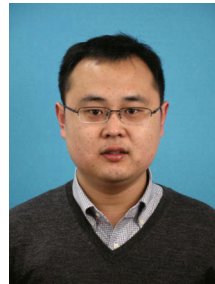
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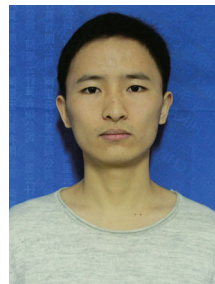
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